Channel Characteristics for 5G Wireless Systems Operating in Millimeter-wave Bands

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***Abstract*—Co-located 4×4 multiple-input multiple-output measurements of link gain, delay spread, and capacity at 24 GHz and 2.55 GHz are compared for an indoor environment consisting of offices, large rooms, and hallways. The results show that link gain at the two frequencies is similar in hallways and connected laboratories after removing the impact of effective antenna aperture but is much lower at 24 GHz in non-line-of-sight scenarios. For all environments, median delay spreads as well as system capacity at a fixed signal-to-noise ratio at 24 GHz are similar to those observed at 2.55 GHz. Ray tracing simulation results show reasonable to good agreement with the measured link gain but tend to provide lower capacity estimates. Overall, the results suggest that bands near 24 GHz may be able to support multiple-antenna communication strategies.**

I. Introduction

The increased availability of wireless devices, breadth of wireless services offered, and demand for higher data rates have combined to place significant pressure on available spectrum in the UHF and microwave bands. This has naturally motivated the community to explore wireless communication at higher frequencies, with millimeter-wave (mm-wave) frequencies being attractive for a number of reasons [1]. While significant work has appeared for communication near 60 GHz, more recent attention has turned to communication in the lower mm-wave bands from 15-38 GHz due to more favorable propagation conditions and lower cost and higher availability of semiconductor components. This work characterizes indoor propagation – including link gain, delay spread, and 4×4 multiple-input multiple-output (MIMO) channel capacity – at 24 GHz in the Clyde Building at Brigham Young University and compares the results to those from co-located measurements at 2.55 GHz and from ray tracing simulations. Results show that frequencies near 24 GHz should be able to support MIMO communication techniques and therefore to enable high spectral efficiency coupled with significantly larger available bandwidths.

II. Measurements and Simulations

The 24 GHz 4×4 MIMO channel sounder, a block diagram for which appears in Fig. 1, uses a switched architecture to sequentially connect all combination of transmit-receive antenna pairs to the sounding system electronics. The 12 GHz local oscillator (LO) uses a phase-locked loop device (ADF4159) to create a frequency modulated continuous wave signal with a bandwidth of 250 MHz. The signal is frequency doubled before being sent to the transmitter via a radio-over-fiber link consisting of an optical transmitter (OT) and receiver (OR) and length of optical fiber (OF). This signal is amplified (PA) and routed through a switch to one of four transmit antennas.

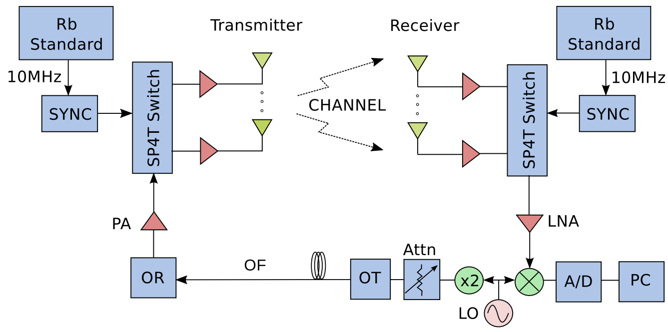

Fig. 1. Block diagram of the 24 GHz channel sounder.

The signal received on the selected receive antenna is routed through the switch, low-noise amplified (LNA), and downconverted using a subharmonic mixer using the 12 GHz LO. The baseband signal is filtered and sampled at 1 MS/s with 16-bit resolution. The SYNC units synchronize the switching, with disciplined Rubidium references providing the clocks. The complete 4×4 channel matrix is acquired in 40 ms. All measurements use omni-directional vertically-polarized quarter-wave monopole antennas with $\lambda/2$ inter-element spacing, where λ is the wavelength.

The transmitter was placed in a main hallway while the receiver was either in a line-of-sight (LOS) arrangement in the same hallway, a non-LOS (NLOS) arrangement around one or two corners in the hallway, or a NLOS arrangement in rooms connected to the hallway. The indoor environment was also modeled with the Wireless InSite tool from Remcom. The tool returns the departure and arrival angle, delay, and gain of each multipath component, allowing MATLAB analysis of the data to determine propagation characteristics. The floor plans used for the simulations included walls, doors, floor, and ceiling. Readily available material parameters were used for the simulations, although generally the conductivity needed to be increased at 24 GHz in order to get better agreement of the link gain between simulations and measurements.

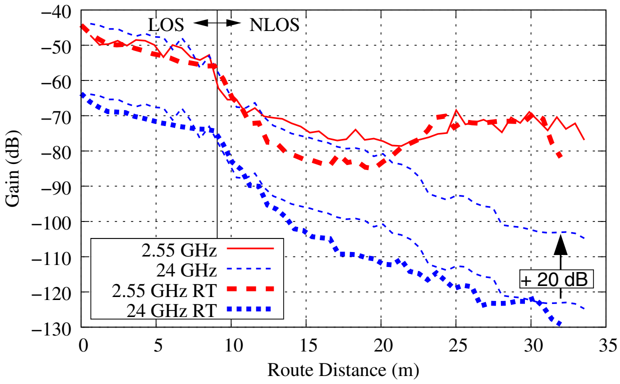

Fig. 2. Link gain for measured data compared with ray-tracing (RT) simulations. The 24 GHz measured data is also shifted by +20 dB to compensate for the effect of aperture loss.

III. Link Gain

Link gain is estimated by averaging the received channel power, obtained by integrating the denoised linear power delay profiles, over all transmit-receive antenna pairs and frequencies. Fig. 2 plots this link gain as a function of receiver position along a hallway. The transition from LOS to NLOS is where the receiver moves around a corner. Since the Friis transmission equation indicates that the received power is proportional to $20 \log_{10} \lambda$ (in dB), the 10-fold increase in frequency between 2.55 GHz and 24 GHz results in a 20 dB reduction in received power. Therefore, we also plot the 24 GHz link gain shifted by +20 dB, which shows that for the first 20 m of the receiver route, the link gains are very similar at the two frequencies when corrected for this aperture loss. At the route distance of 20 m, however, we see the two results deviate. At this point, the receiver moves around a second corner, and therefore some of the propagation may be moving more through walls than through the hallway. In this case, the 24 GHz signal experiences excess loss. Other results (not shown) reveal similar excess loss when the receiver is placed in a room adjacent to the hallway, suggesting that the transmission loss through the walls is higher at 24 GHz than at 2.55 GHz. These results also show that the ray-tracing (RT) simulations offer reasonably good predictions of the link gain at both frequencies.

Fig. 3 plots the path loss (PL) from all measurements separated into LOS and NLOS cases, computed as

$$\mathrm{PL}(f,d)\ [\mathrm{dB}] = G_{\mathrm{T}} + G_{\mathrm{R}} - G(f,d), \tag{1}$$

where $G(f,d)$ is the link gain at frequency f and distance d and G_{T} and G_{R} are the transmit and receive antenna gains (assumed to be 5 dBi for quarter-wave monopoles). The solid curves are the best fit to the mean close-in (CI) path-loss model [2]

$$\mathrm{PL}^{\mathrm{CI}}(f,d)\ [\mathrm{dB}] = \mathrm{PL}(f,d_0) + 10n \log_{10}\left(\frac{d}{d_0}\right), \tag{2}$$

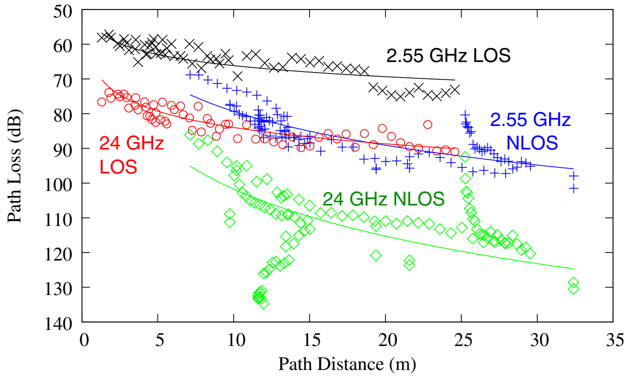

Fig. 3. Path loss versus path distance for all measurements, with solid lines showing the best fit CI model.

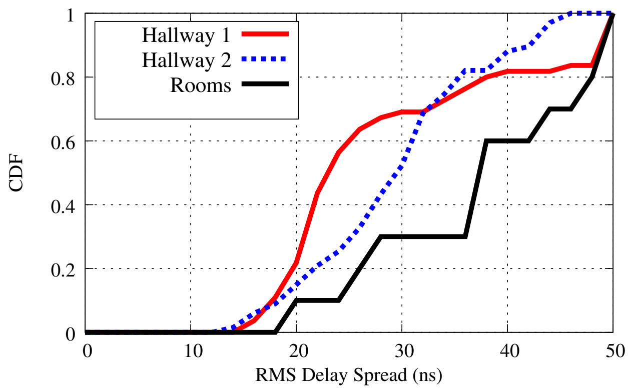

Fig. 4. CDFs of RMS delay spread for 24 GHz measured data in three different scenarios.

where $d_0 = 2.5$ m. As expected, the CI model predictions are relatively accurate for LOS data but not for NLOS data, especially at 24 GHz.

IV. Delay Spread

Fig. 4 plots CDFs of the RMS delay spread for three different measurements. In the first two, the receiver is moved in the same hallway as the transmitter, with 'Hallway 1' and 'Hallway 2' indicating moving down the hallway in opposite directions away from the transmitter location. The designation 'Rooms' means the ensemble of data when the receiver is placed in rooms adjacent to the hallway occupied by the transmitter. The plots reveal that RMS delay spread in this environment ranges from 10 to 50 ns, with median values ranging between 20 to 35 ns, similar to those of indoor 28 GHz channels reported in the literature [3], [4]. The peak delay spread of 50 ns is smaller than peak values observed near 2.4 GHz reported elsewhere [5], which often range from 50 to 150 ns.

V. MIMO Capacity

Fig. 5 plots the CDF of capacity for all measurements and ray tracing results computed using

$$C = \frac{1}{N_{\mathrm{F}}} \sum_{n=1}^{N_{\mathrm{F}}} \log_2 \left| \mathbf{I} + \frac{\rho}{N_{\mathrm{T}}} \mathbf{H}^{(n)} \mathbf{H}^{(n)H} \right|, \tag{3}$$

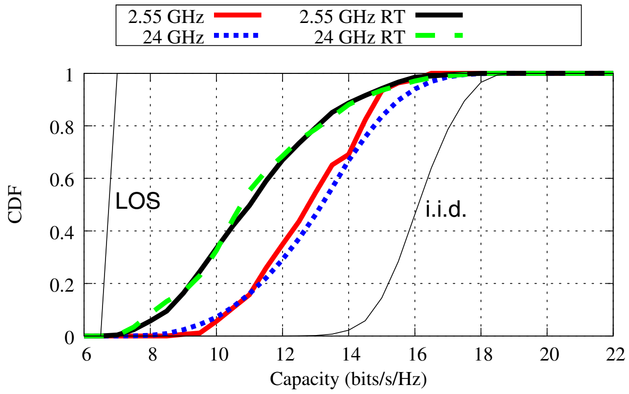

Fig. 5. Capacity CDFs for all measured and ray tracing result. Capacity CDFs for simulated single-path (LOS) and i.i.d. channels are also shown for comparison.

where N_F is the number of frequency samples, $N_\mathrm{T} = 4$ is the number of transmitters, $\mathbf{H}^{(n)}$ is the normalized channel matrix measured at the nth frequency sample, ρ is the signal-to-noise ratio (SNR), and $|\cdot|$ is the determinant. A system employing transmit power control is assumed with $\rho = 15$ dB for all results, which removes the impact of link gain variability. The results at 24 GHz are very similar to those at 2.55 GHz, suggesting that the multipath richness at the two frequencies is also similar. The results also show that ray tracing under-predicts capacity, possibly because many of the scatterers – such as furniture – present in the measurement are not included in the simulations.

VI. Conclusion

This work compares 4×4 MIMO measurements at 24 and 2.55 GHz with result from ray tracing simulations. The measurements indicate that the MIMO capacity is remarkably similar at the two widely separated frequencies, suggesting that sufficient multipath is available at 24 GHz to support MIMO communications. The results also demonstrate that in LOS or situations where waveguiding appears to be a dominant propagation mechanism, the link gain is very similar at the two frequencies when compensation for the aperture loss with frequency is applied. Overall, the results suggest that indoor communications at lower mm-wave frequencies may be able to use multi-antenna signaling techniques to improve reliability and throughput.

References

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